Towards Predicting Transonic Aerodynamics using Wall Modelled Large Eddy Simulations

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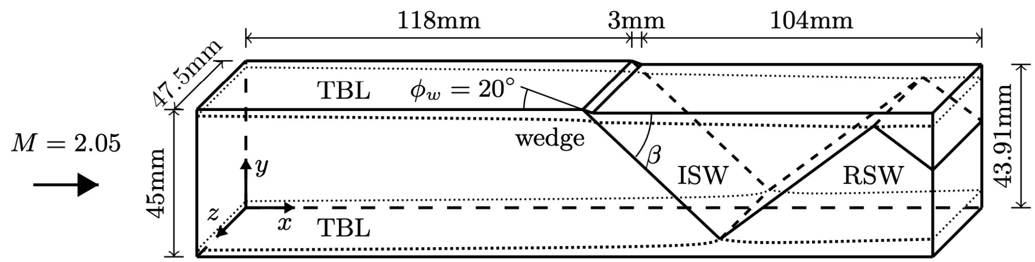
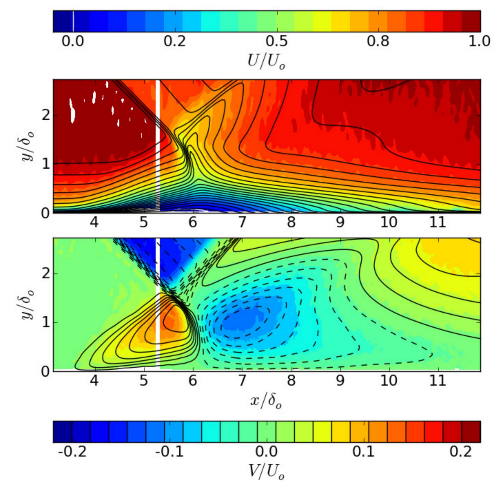
Background

- Push for use of CFD towards **Certification and Qualification by Analysis** (CQbA) (Slotnick et al., 2013)
- CFD using **RANS closures** typically only **calibrated** for small regions of the operating envelope (example: high speed cruise)
- Limited success for RANS seen in:
  - Smooth body and geometry induced separation in high-lift configurations (High Lift Prediction Workshops)
  - Side-of-body corner flow separation (Juncture Flow Workshop)
  - Shock-induced flow separation and buffet (Drag Prediction Workshops)
- <u>Focus of the present work</u>: Assessment **of Equilibrium Wall Modelled Large Eddy Simulations** for predicting aerodynamic loads leading up to and beyond **shock-induced separation** (buffet boundary)

Background – Canonical SBLI

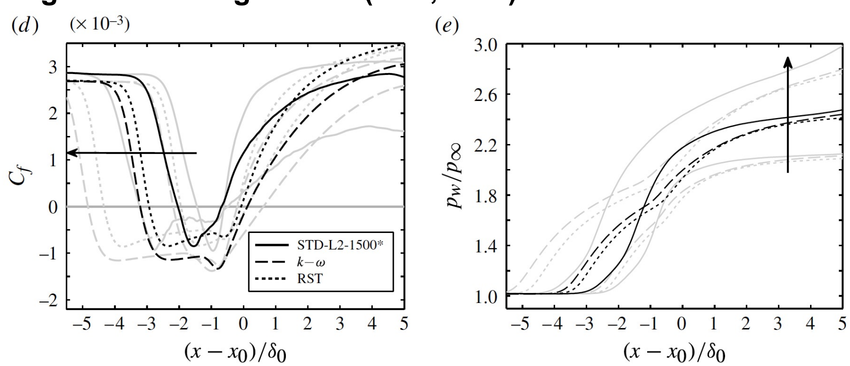
- Shock-boundary layer interactions typically studied using OSTBLI framework:
  - DNS by Pirozzoli and Bernardini (AIAA J., 2011) ($Re_\theta \approx 2300; M_\infty = 2.28$)
  - Large database of wall-resolved LES by Morgan et al. (J. Fluid Mech., 2013) ($Re_\theta \leq 4800; M_\infty = 2.28$)
  - Non-equilibrium WMLES by Kawai & Larsson (PoF, 2013) ($Re_\theta \approx 50{,}000; M_\infty = 1.69$)
  - Equilibrium WMLES by Bermejo-Moreno et al. (J. Fluid Mech., 2014) ($Re_\theta \approx 14{,}000; M_\infty = 2.05$)

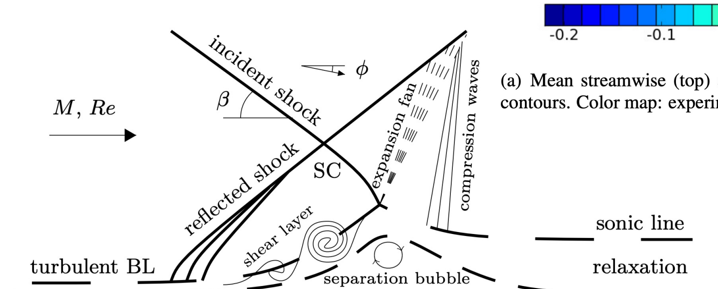




(a) Mean streamwise (top) and wall-normal (bottom) velocity contours. Color map: experimental data; lines: WMLES.

Figure from Morgan et al. (JFM, 2013)

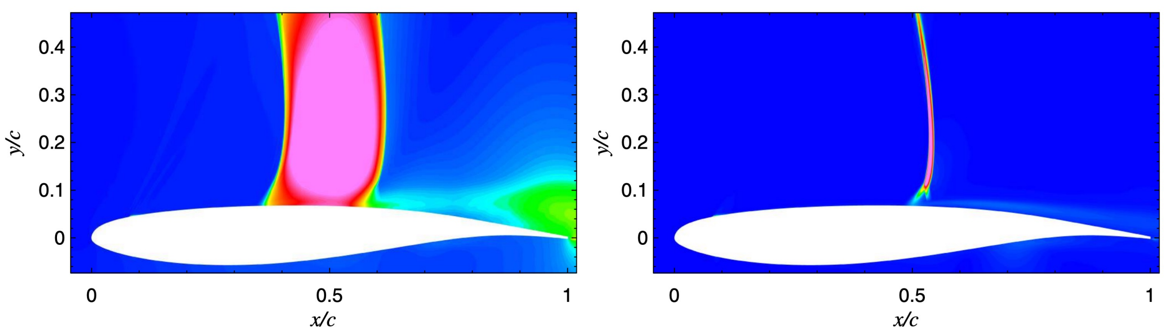




Figures taken from Bermejo-Moreno et al. (JFM, 2014)

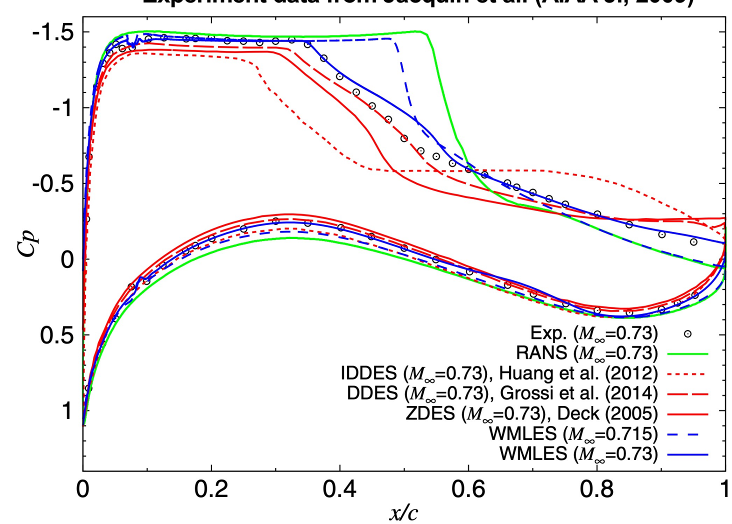
Background – Transonic buffet on Airfoils

- Buffet conditions:
    - Self-sustained low-frequency shock oscillations marked by shock induced flow separation; for airfoils dominated by a single main frequency (same order as low-frequency elastic modes)
    - Long history of URANS application and analysis (Lee, 2001): large sensitivity to numerical formulation along with closure model
    - Hybrid RANS/LES (Deck et al. 2005) and more recently WMLES (Fukushima & Kawai, 2018) has shown some promise



a) Buffet condition ($M_\infty = 0.73$) b) Nonbuffet condition ($M_\infty = 0.715$)

Experiment data from Jacquin et al. (AIAA J., 2009)



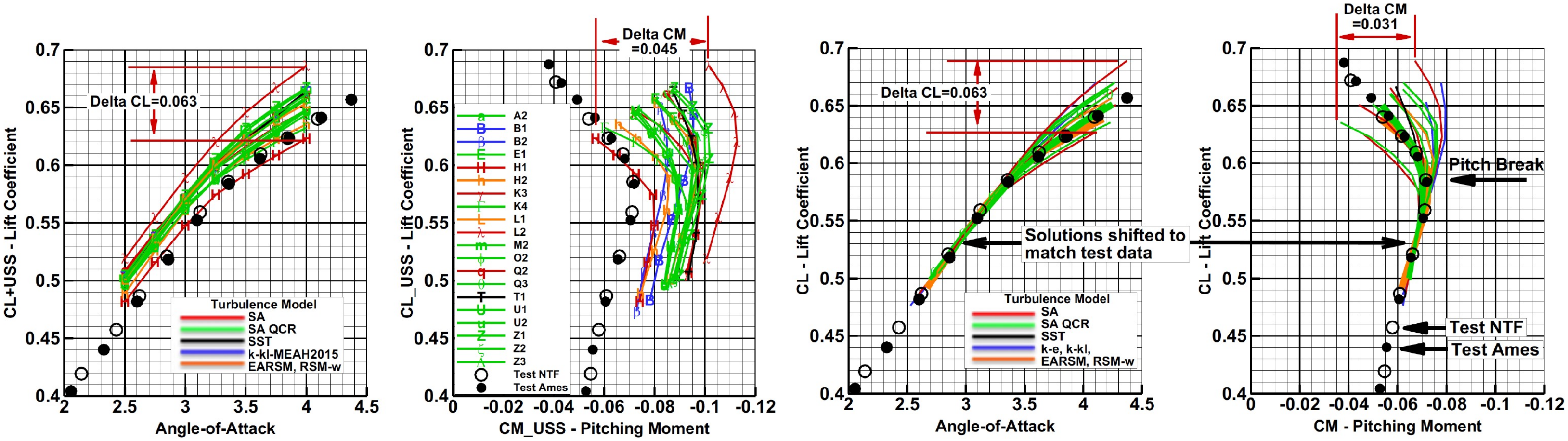
Figures taken from Fukushima & Kawai (AIAA J., 2018)

Key Questions – SBLI on aircraft configuration

1. **Can WMLES be used to accurately predict skin friction drag at cruise conditions?**
   - RANS models accurately predict skin friction drag at cruise conditions where it is a significant fraction of total drag; Can WMLES be equally predictive?

Key Questions – SBLI on aircraft configuration

1. Can WMLES be used to accurately predict skin friction drag at cruise conditions?
2. **Can WMLES model the progression of shock-induced separation? This involves the predictability of the following two metrics:**
   A. Accurate lift-curve slope and the pitching moment in the linear regime representing the change in shock location with changes in the angle of attack.
   B. Accurate prediction of the pitch break representing onset of shock-induced flow separation that occurs at $c_L \approx 0.6$, and accurate prediction of the lift curve slope beyond this point.



(a) Raw data (b) Shifted data

Figure taken from Tinoco (2020) [AIAA-2020-2745]

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3. **Can constant/static coefficient subgrid scale modeling be used for external aerodynamics involving predictive simulations of shock-boundary layer interactions?**
   - Do we need a Germano-type Dynamic procedure for predictability, or is a constant coefficient SGS closure acceptable?

Key Questions – SBLI on aircraft configuration

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3. Can constant/static coefficient subgrid scale modeling be used for external aerodynamics involving predictive simulations of shock-boundary layer interactions?
4. **Can WMLES accurately predict the buffet intensity measured using the wing root bending moment seen in experiments by Balakrishna & Acheson (2011)?**
5. **Can WMLES accurately predict the tonal and broadband character of pressure fluctuations near the trailing edge as seen in experiments of Jacquin et al. (2009)?**

Key Questions – SBLI on aircraft configuration

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Questions 1-3 addressed in this talk; 4 and 5 will be addressed in the future

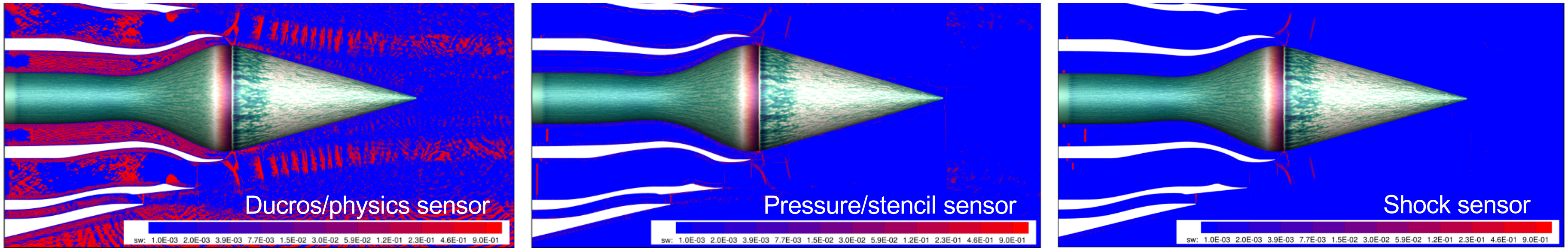
Outline

- Numerical formulation
- Wall-modeling for transonic flows
- Structured overset grid systems
- Problem 1: Wing-only configuration
- Problem 2: Wing-body configuration with static wing deflections
- Computational cost
- Summary and Outlook

All computational research was performed using the **structured curvilinear overset formulation** within the **Launch, Ascent, and Vehicle Aerodynamics (LAVA) framework**

Numerical formulation

- Curvilinear Navier-Stokes with Eddy Viscosity SGS closure
  - Mid-point interpolation with blending between 4th order central schemes and 3rd order WENO-JS; HLL Riemann solver; 3rd order upwind interpolation at overset fringe points
  - 2nd order mid-point viscous flux (staggered operators)
  - 2nd order accurate staggered divergence-of-flux operator
  - 3rd order TVD-RK3 scheme
- Shock sensor is a combination of:
  - Ducros-type sensor: {shock, acoustics} <-> {turbulence}
  - Pressure/stencil-sensor (Tramel et al., 2009, AIAA): {shock, turbulence} <-> {acoustics}



- Shock sensor switched off near leading edge where BL (numerical) transition occurs

Wall Modeling for Transonic Flows

- Compressibility effects in wall-modeling (**adiabatic conditions**)
  - Recent work by Iyer & Malik (PRF, 2019) – no special treatment (scaling, damping, etc.) needed for adiabatic flows for Mach numbers as high as 2
  - y+ definition: Current work uses wall-properties
  - Viscous/buffer layer damping: Wall function of Musker (1979) is used, instead of van Driest damping with an ODE solve

- Is equilibrium modeling appropriate for the flow regime being considered?
  - Common misconception regarding the "Equilibrium hypothesis":

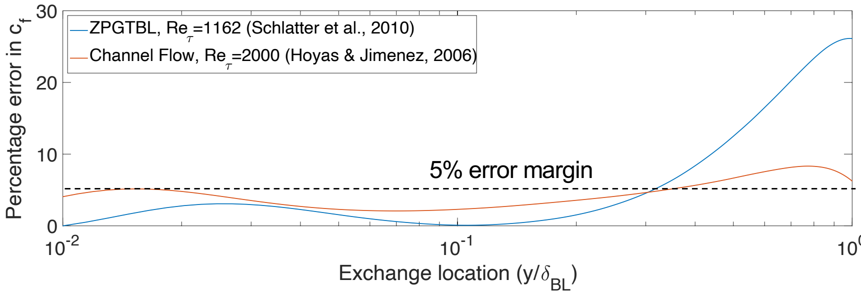
$$\frac{\partial < P >}{\partial x_s} \approx 0$$

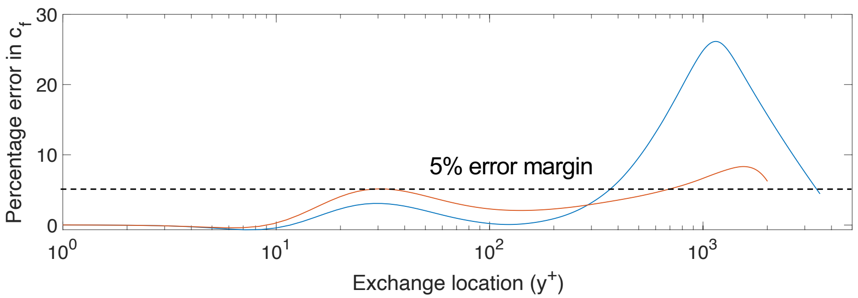
  - Actual assumption:

$$\frac{\partial < P >}{\partial x_s} + \frac{\partial < u_s u_j >}{\partial x_j} - Lateral\ Diffusion\ \approx 0$$

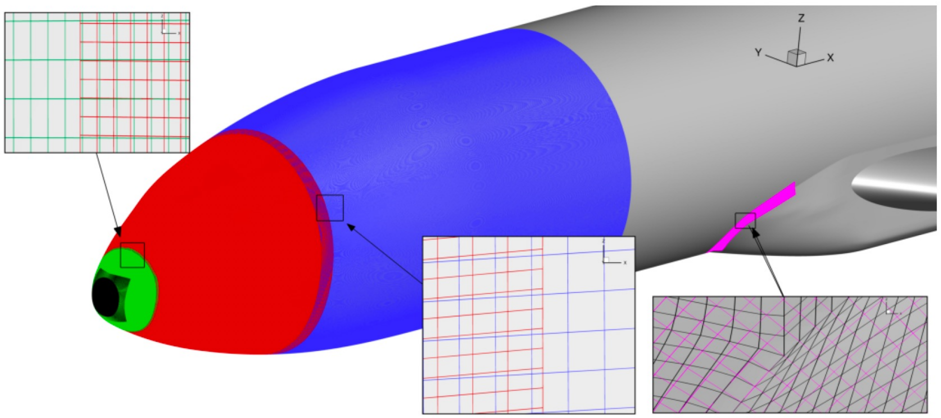
  - Equilibrium assumption fails if:
    - Reynolds stresses under-resolved or erroneous: Need non-dissipative numerics
    - Large aspect ratio grids used in non-equilibrium regions of the flow (streamwise gradients are erroneous, large geometric anisotropy in resolved stress)
  - Recent assessment by Coleman et al. (2015) quantifies pressure-gradient effects on mean velocity; limited sensitivity observed at $y^+ \approx 50$ ($U^+ \approx 14 - 16$)

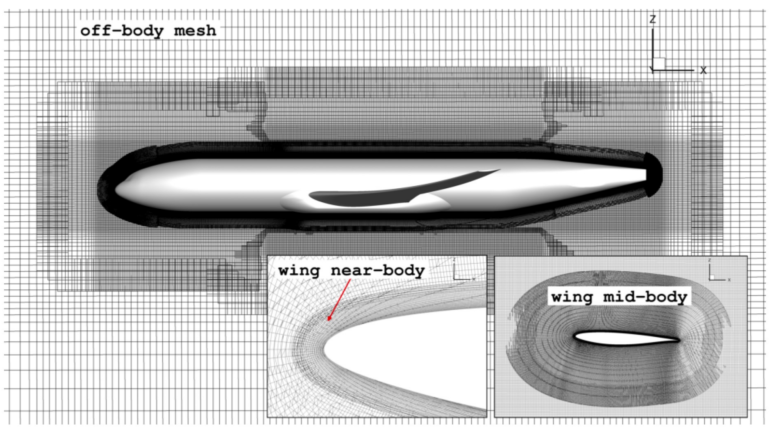
- While compressibility effects occur in the outer potential flow, the TBL turbulence is most certainly incompressible (negligible pressure-dilatation correlations) -> **No special considerations for SGS modeling**

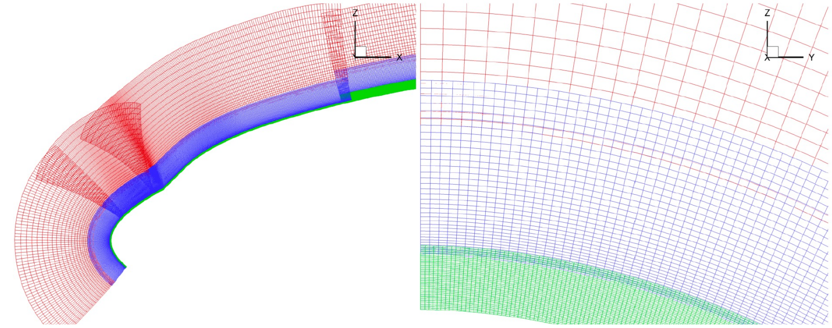


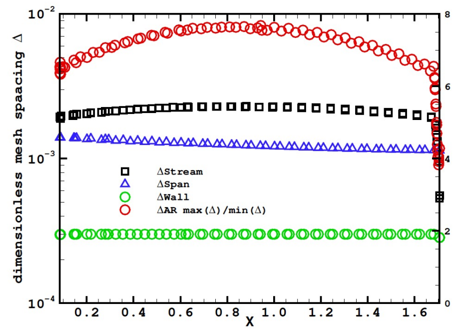


Overset grid system

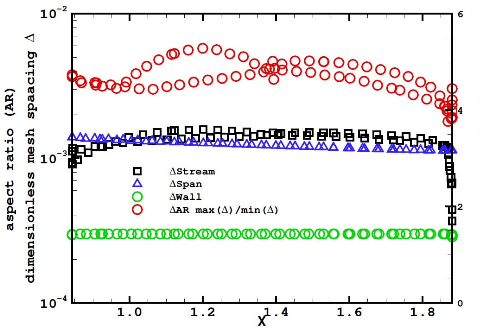




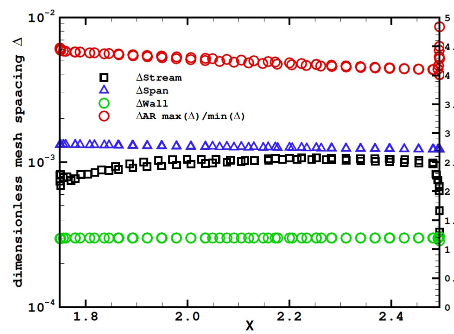




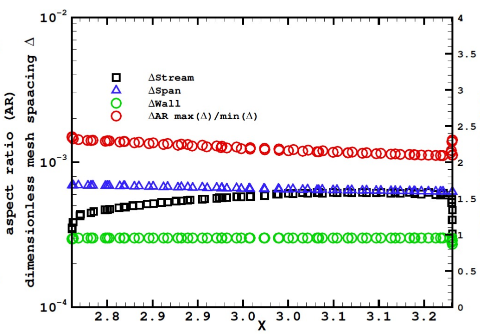
(a) $\eta = 0.05$



(b) $\eta = 0.30$

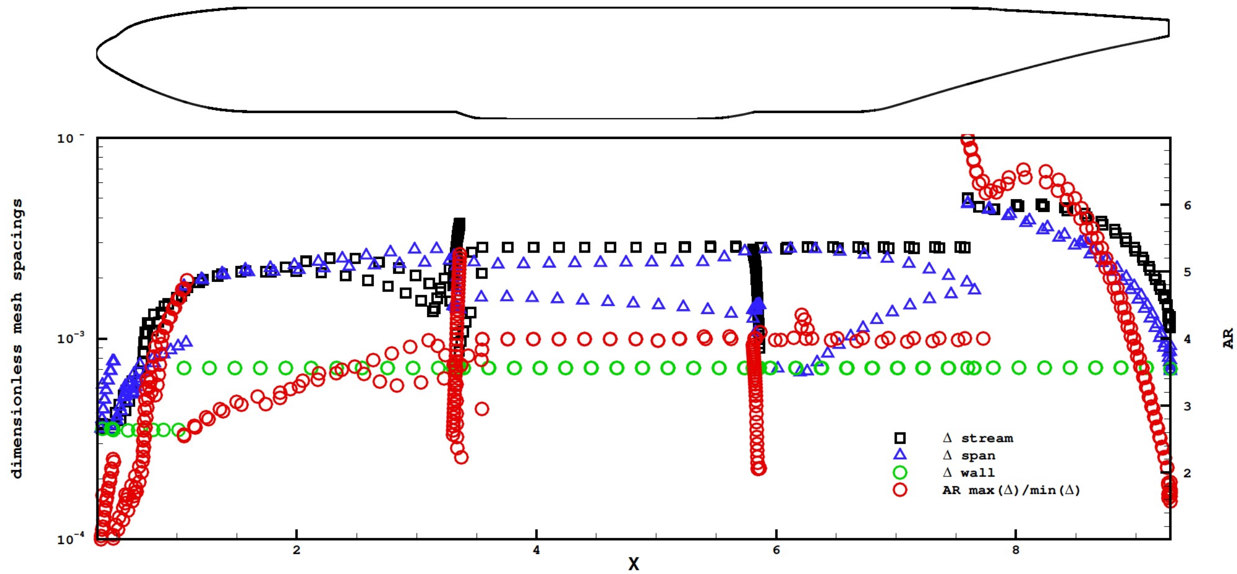


(c) $\eta = 0.60$



(d) $\eta = 0.95$

Overset grid system

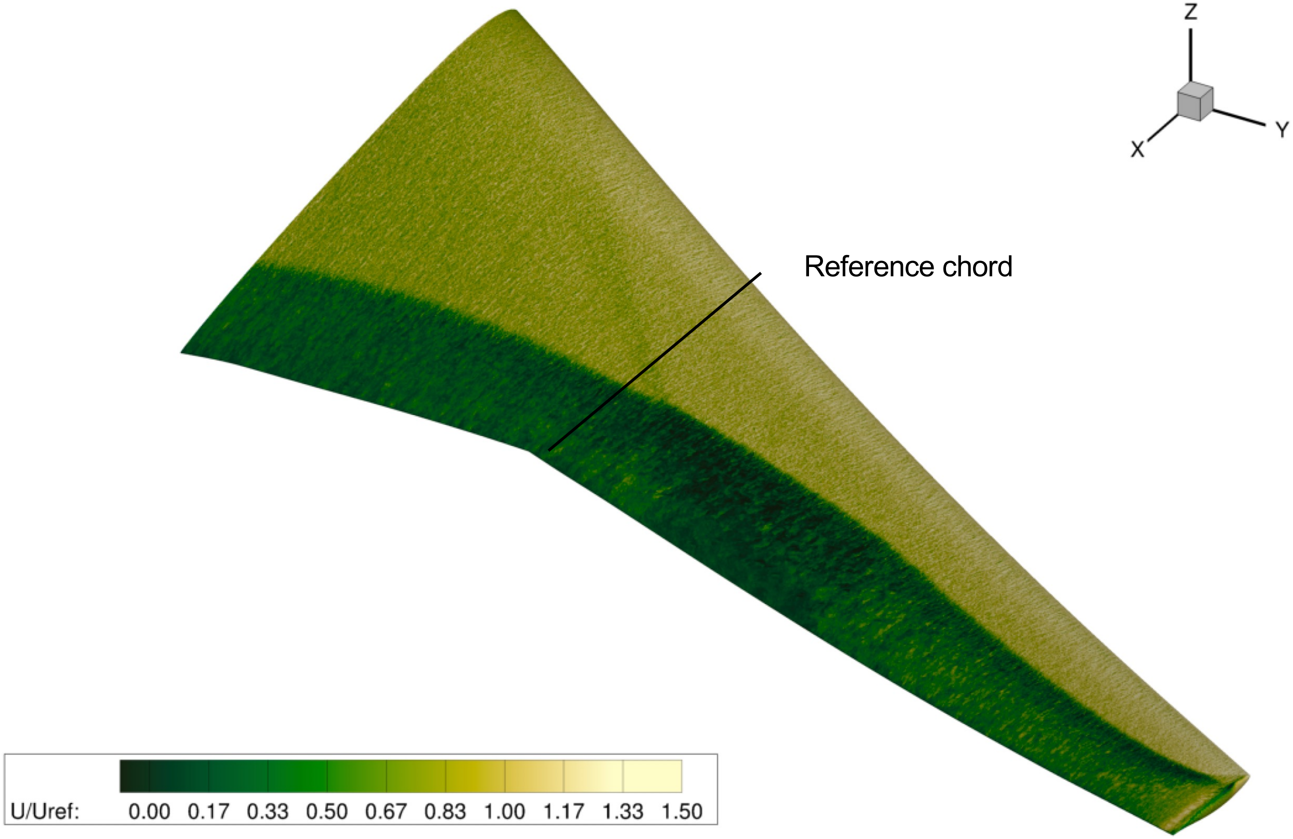


Total grid points (in Million)

Mesh Type	Fuselage	Juncture	Wing	Off-body	Total points
Wing-body (full-span)	244	14	402	22	682
Wing-only	-	-	166	40	206

Problem 1: $Re_c = 5\times10^6; M = 0.85$

- Configuration 1: Wing-only case; rigid wing; $\alpha = 1^0 - 5.25^0$ [Undeflected wing from DPW6]

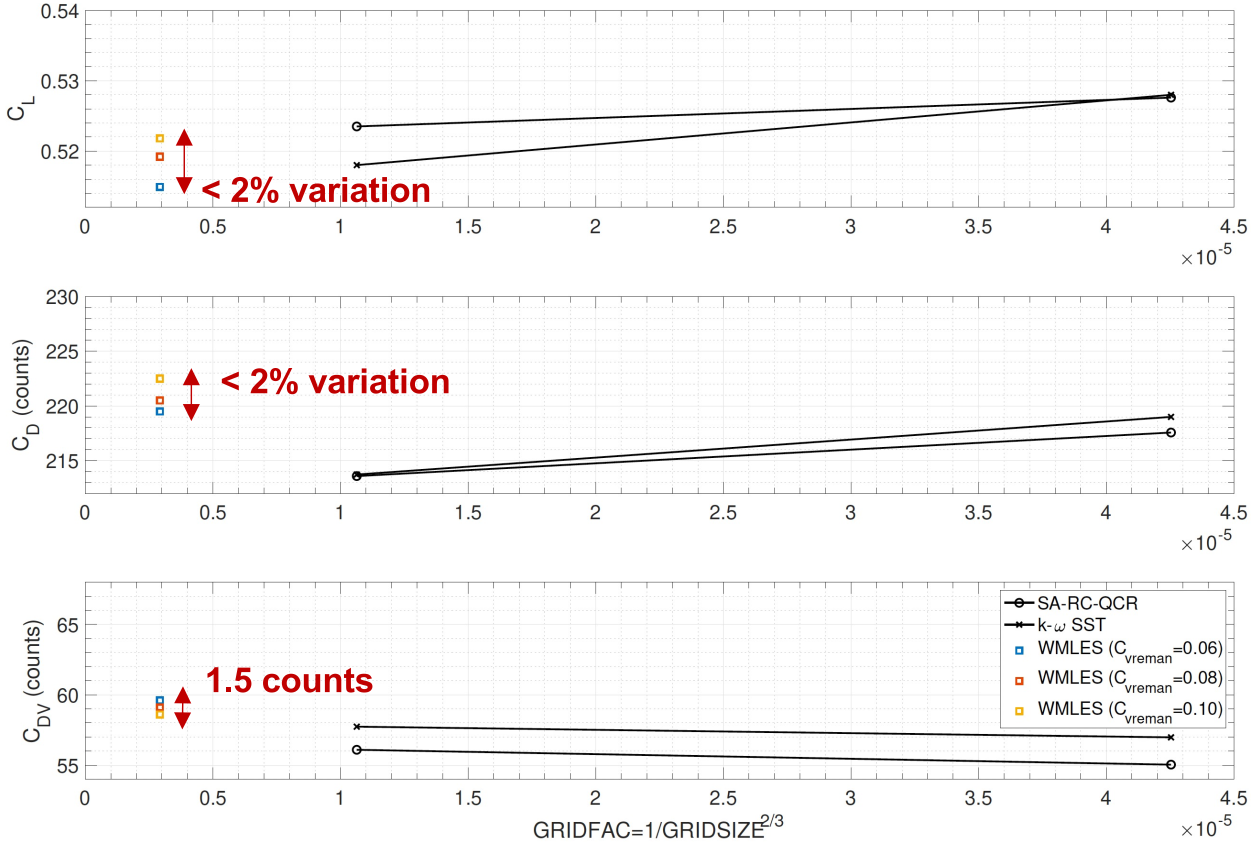


Streamwise velocity at distance $10^{-4}C_{ref}$ from surface

Angle of attack, $\alpha = 4.25^0$

Problem 1: Wing – only configuration

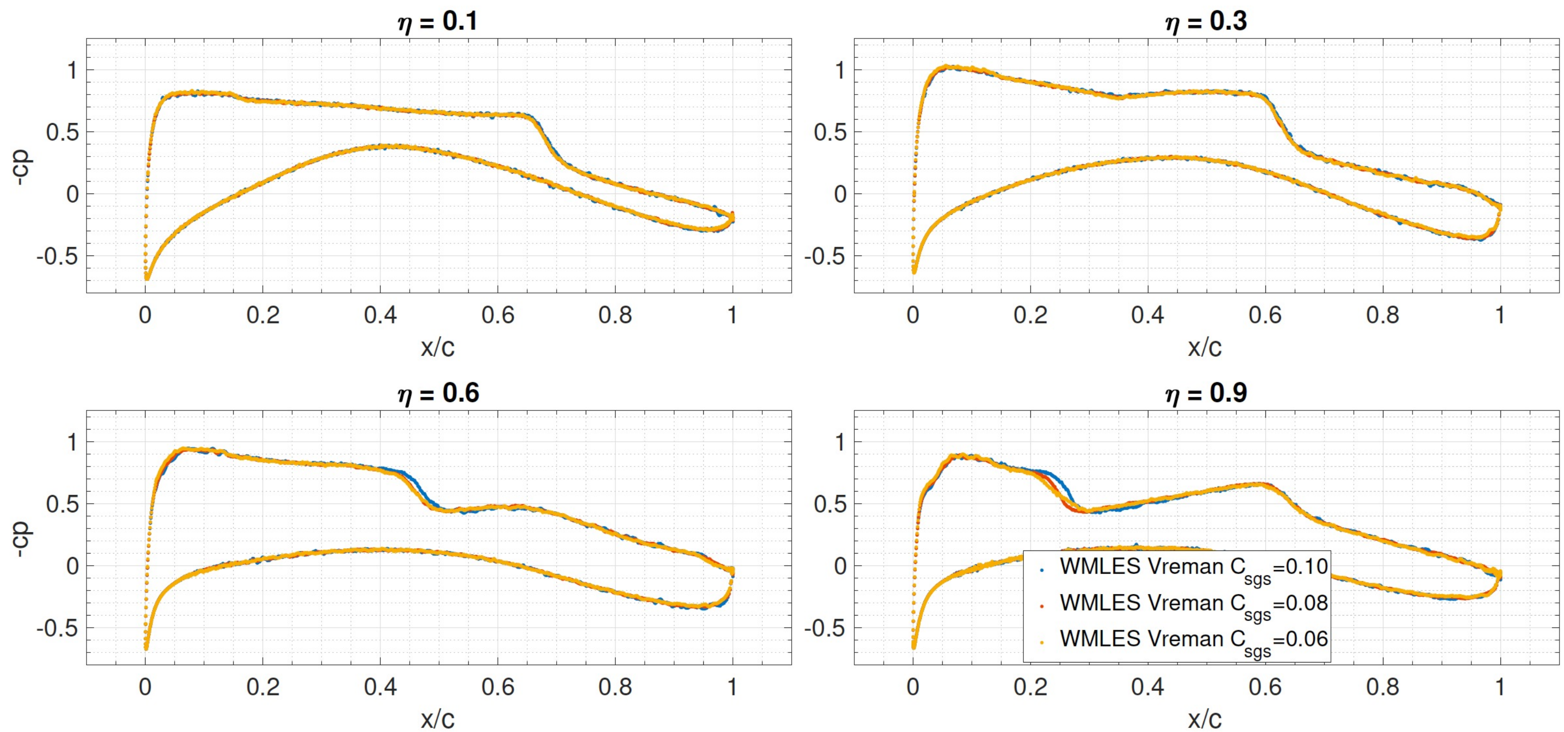
- Cruise-point: $\alpha = 2.5^0$



- SGS Model constant related uncertainty of the same order as RANS model type uncertainty at cruise

Problem 1: Wing – only configuration

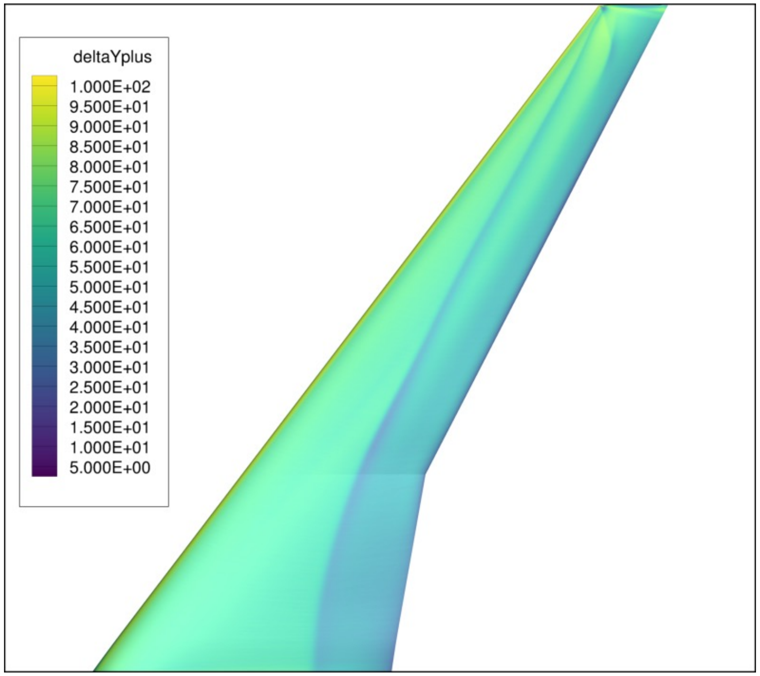
- Cruise-point: $\alpha = 2.5^0$



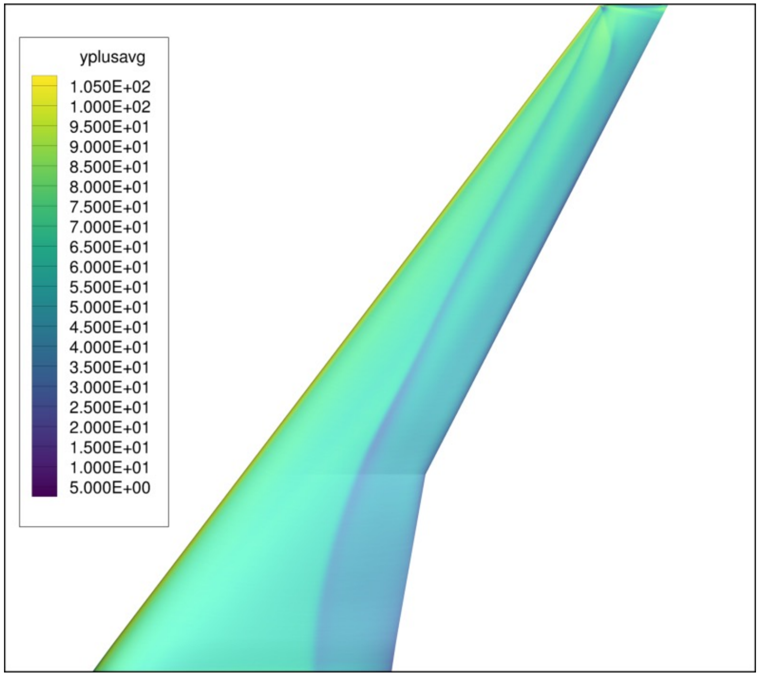
- Little sensitivity to SGS model constant; some minor sensitivity to shock location outboard

Problem 1: Wing – only configuration

- Wall normal spacings in viscous units (Suction side)



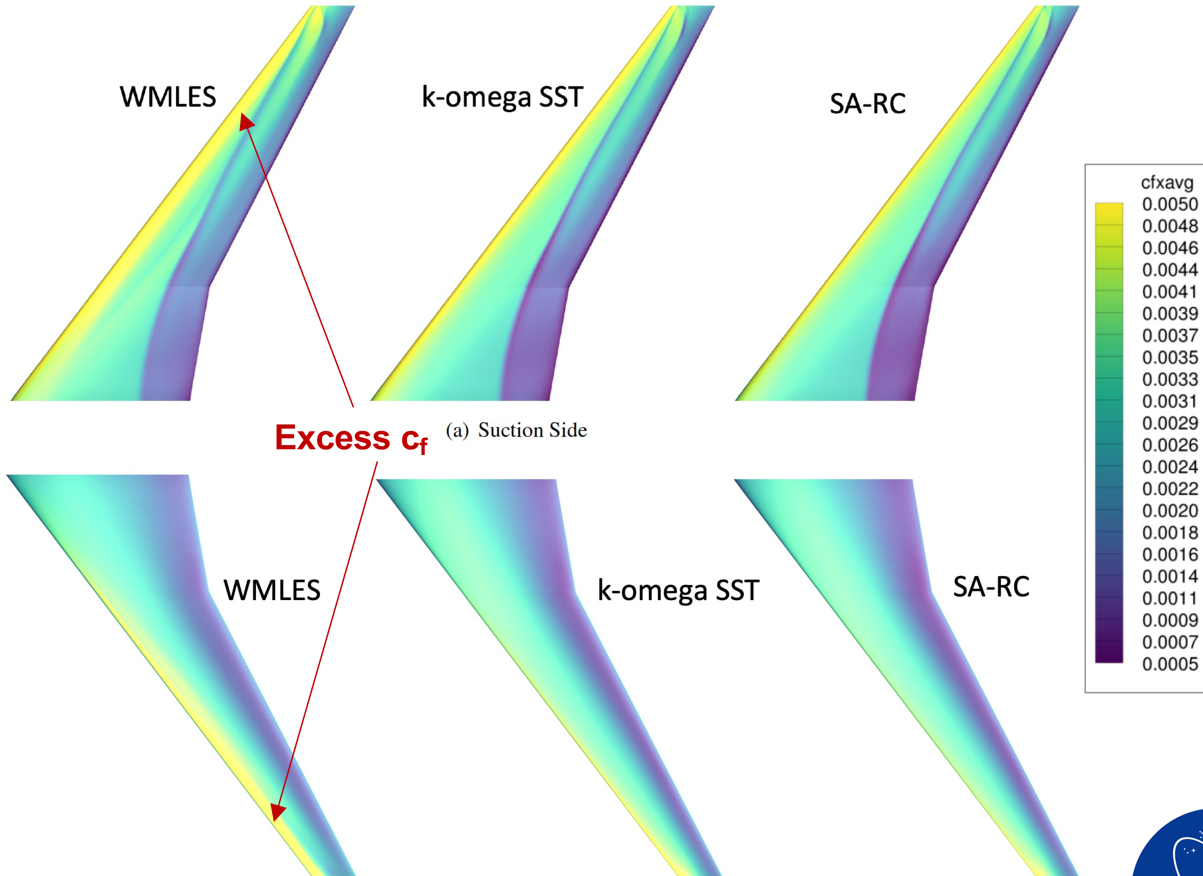
$$y^{+} = \frac{< u_{\tau} > \Delta_{y}}{< \nu_{wall} >}$$



$$y^{+} = < \frac{u_{\tau} \Delta_{y}}{\nu_{wall}} >$$

Results: Wing – only configuration

- Cruise-point: $\alpha = 2.5^0$, $c_{sgs} = 0.06$



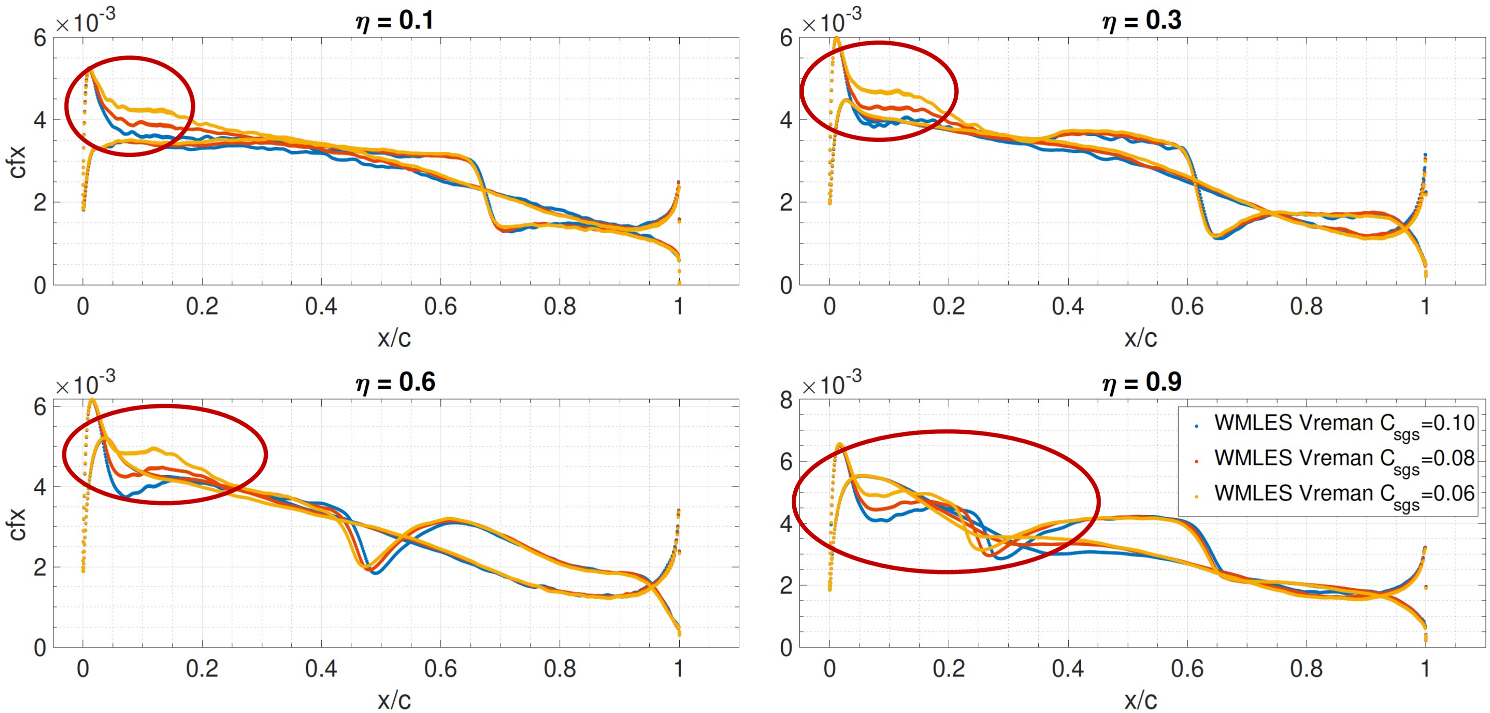
(a) Suction Side

(b) Pressure Side

- WMLES overpredicts skin friction in the transitional parts of the BLs
- RANS model sensitivity also seen near leading edge

Problem 1: Wing – only configuration

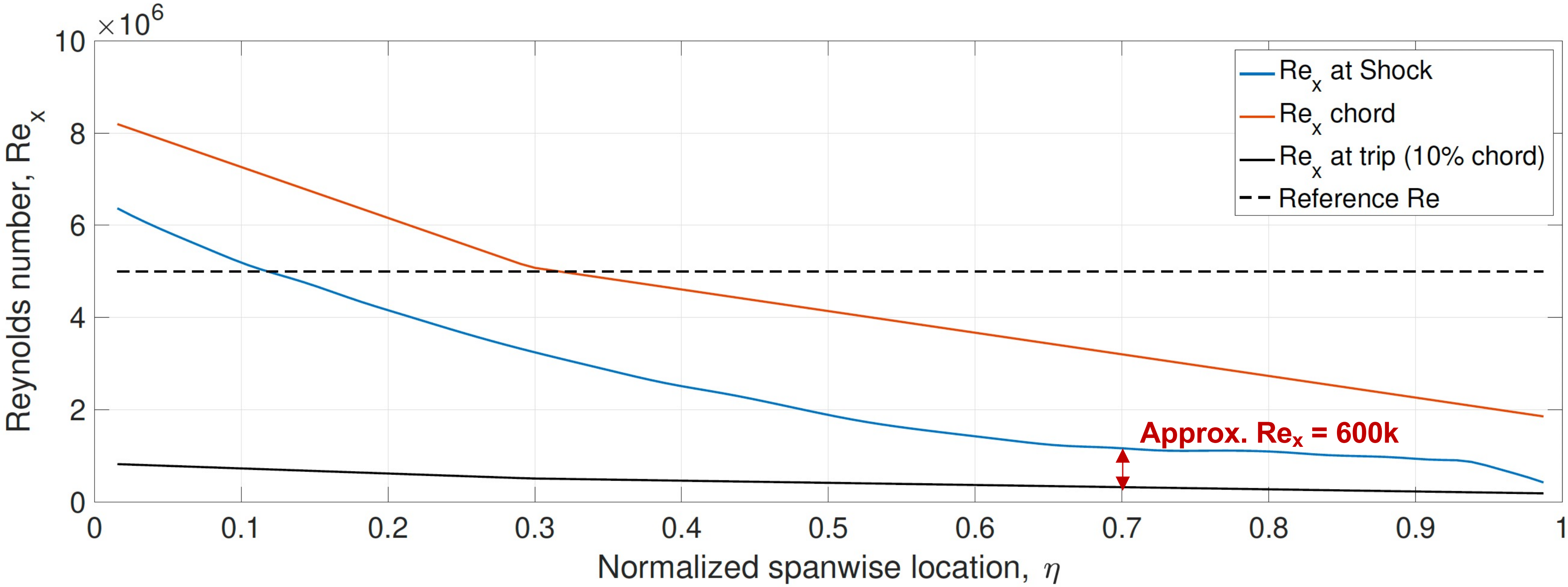
- Cruise-point: $\alpha = 2.5^0$



- SGS model sensitivity seen in transitional sections near leading edge; More relevant outboard

Problem 1: Wing – only configuration

- Cruise-point: $\alpha = 2.5^0$



- Outboard Reynolds numbers are not high -> BLs interact with the shock prior to fully transitioning

Problem 1: Wing – only configuration

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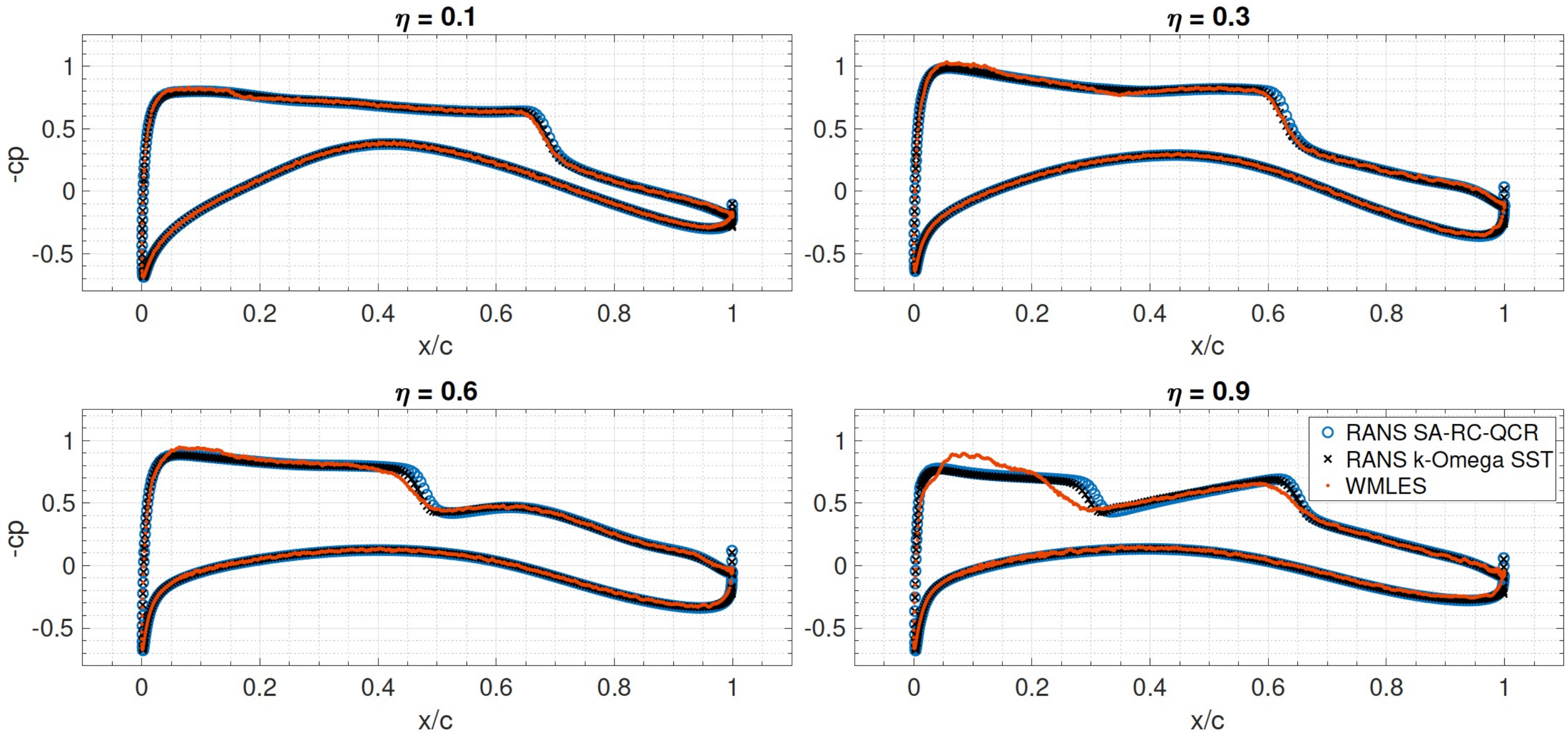
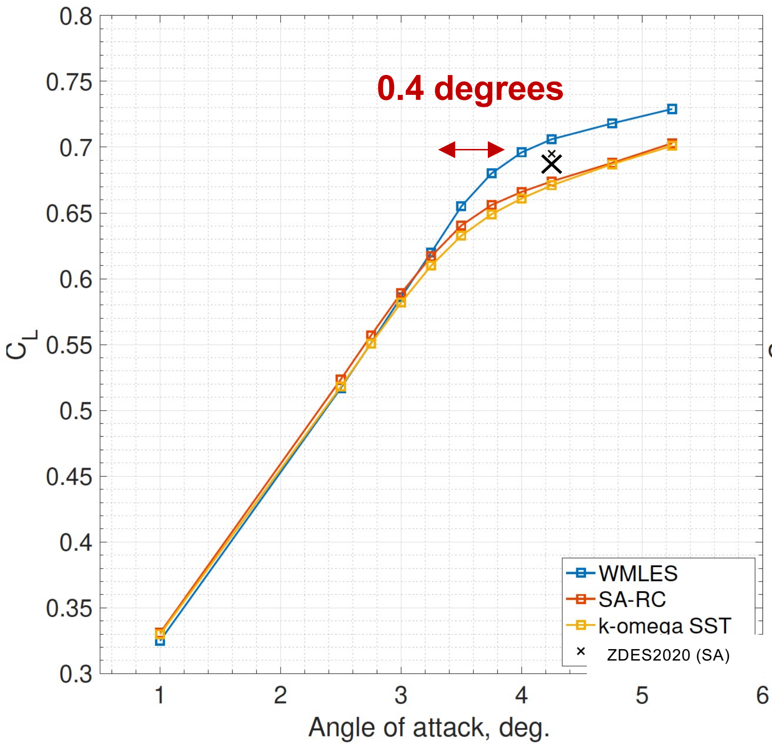


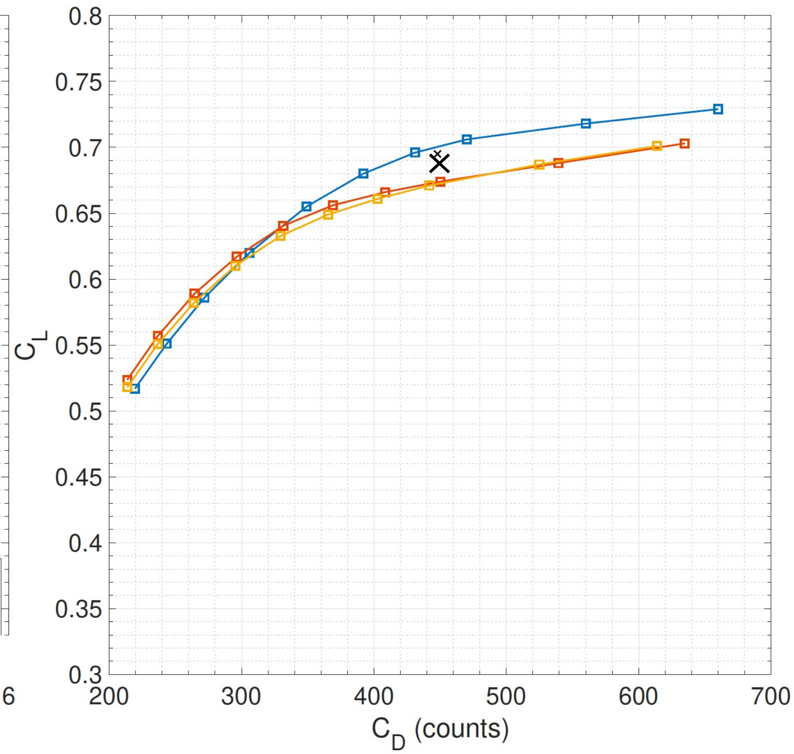
- RANS and LES agree quite well with some differences seen near wing tips

Problem 1: Wing – only configuration

- Lift and Drag curves

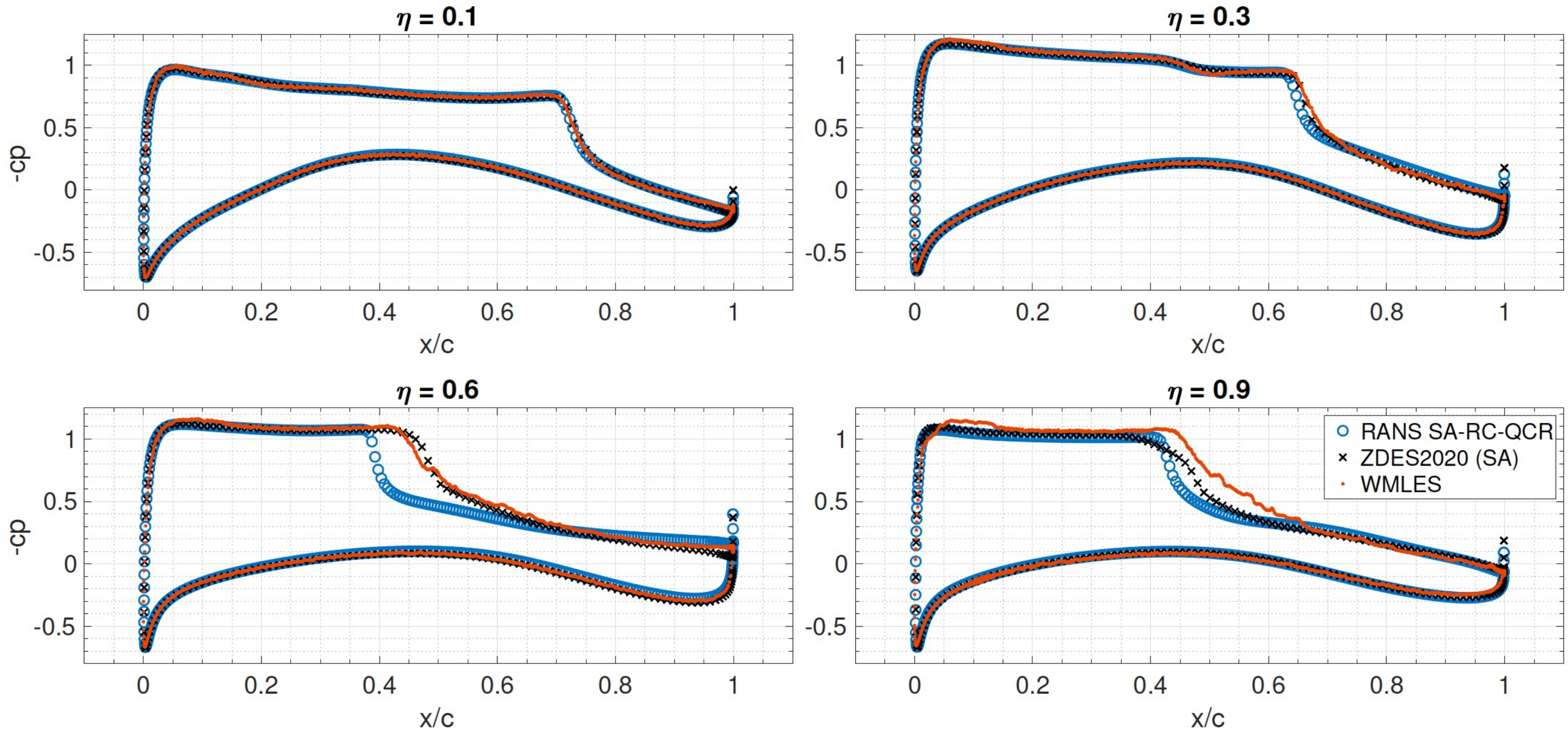
ZDES2020 refers to "enhanced protection" developed by Deck & Renard (JCP, 2020). DES used SA closure without RC corrections on the coarse RANS mesh.





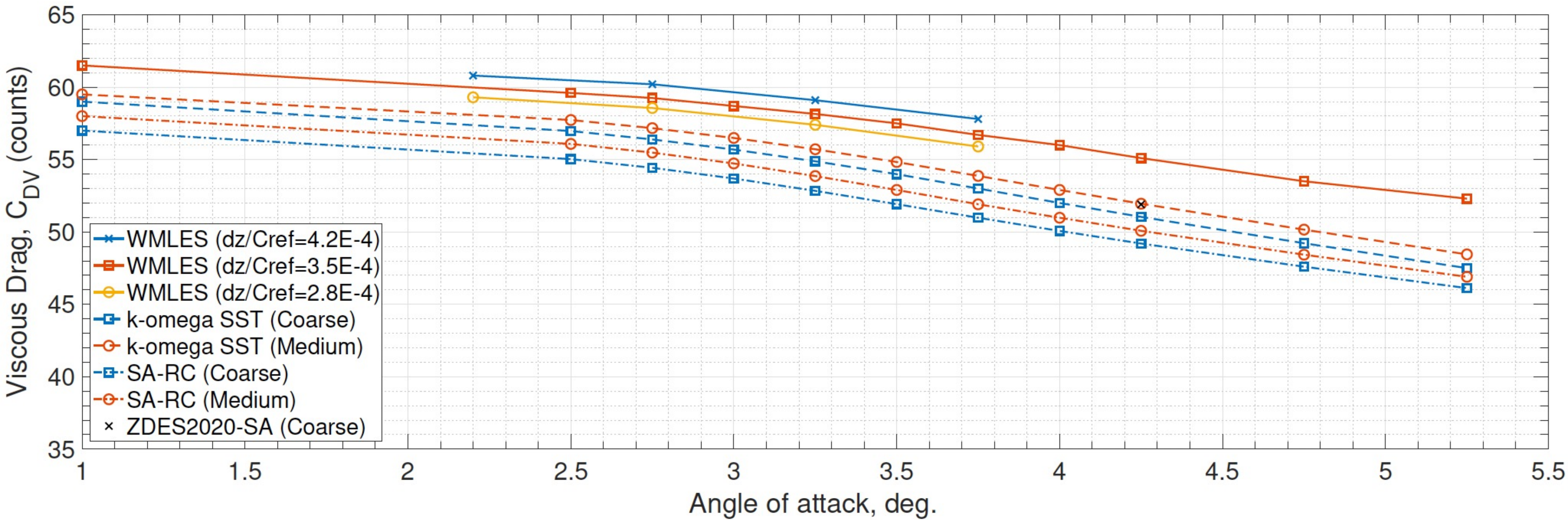
Problem 1: Wing – only configuration

- $\alpha = 4.25^o$



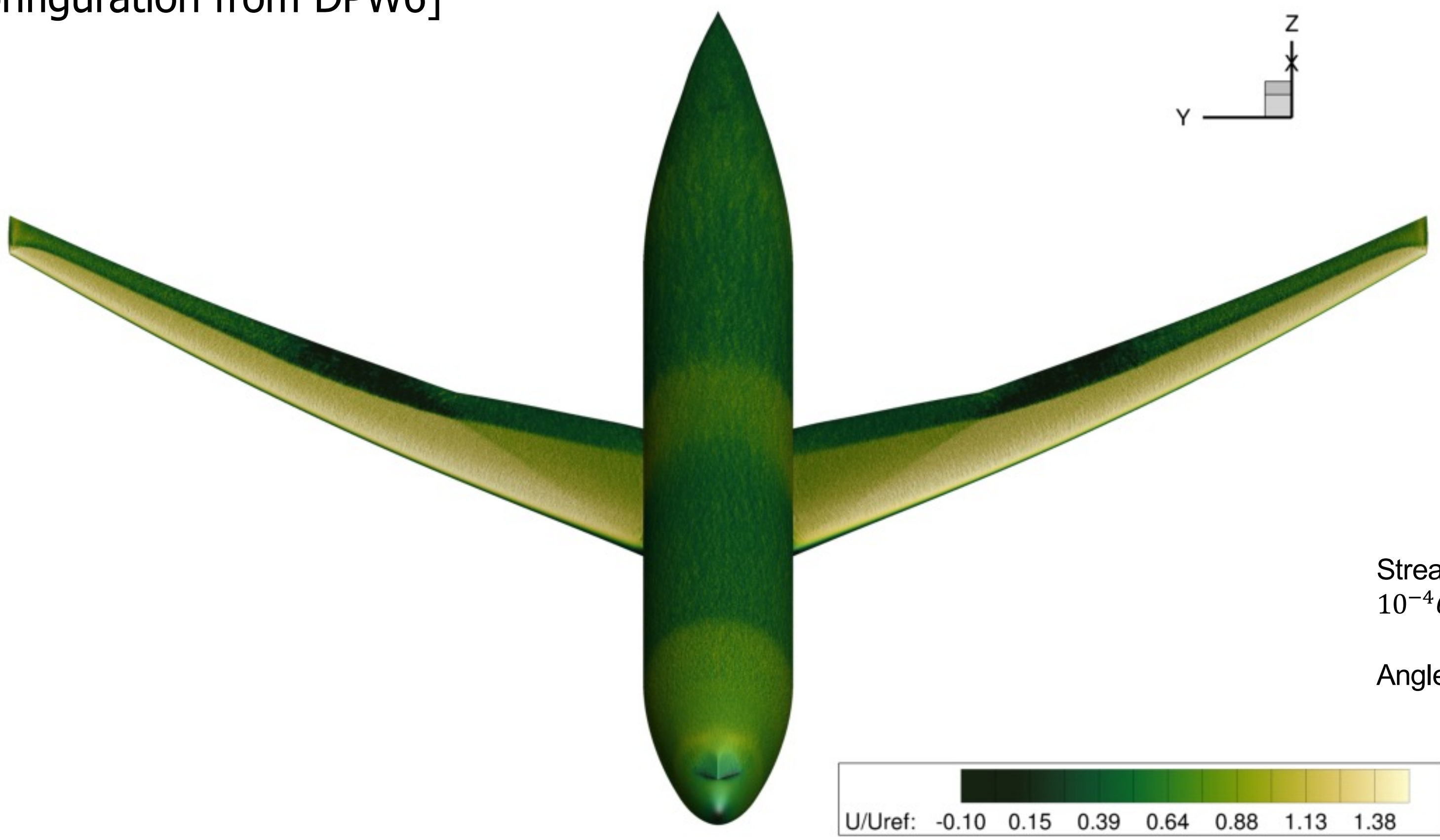
Problem 1: Wing – only configuration

- Grid sensitivity to skin friction



Problem 2: $Re_c = 5\times10^6; M = 0.85$

- Configuration 2: Wing-body case; static aeroelastic deflections; $\alpha = 2.75^0 - 4^0$ [Configuration from DPW6]

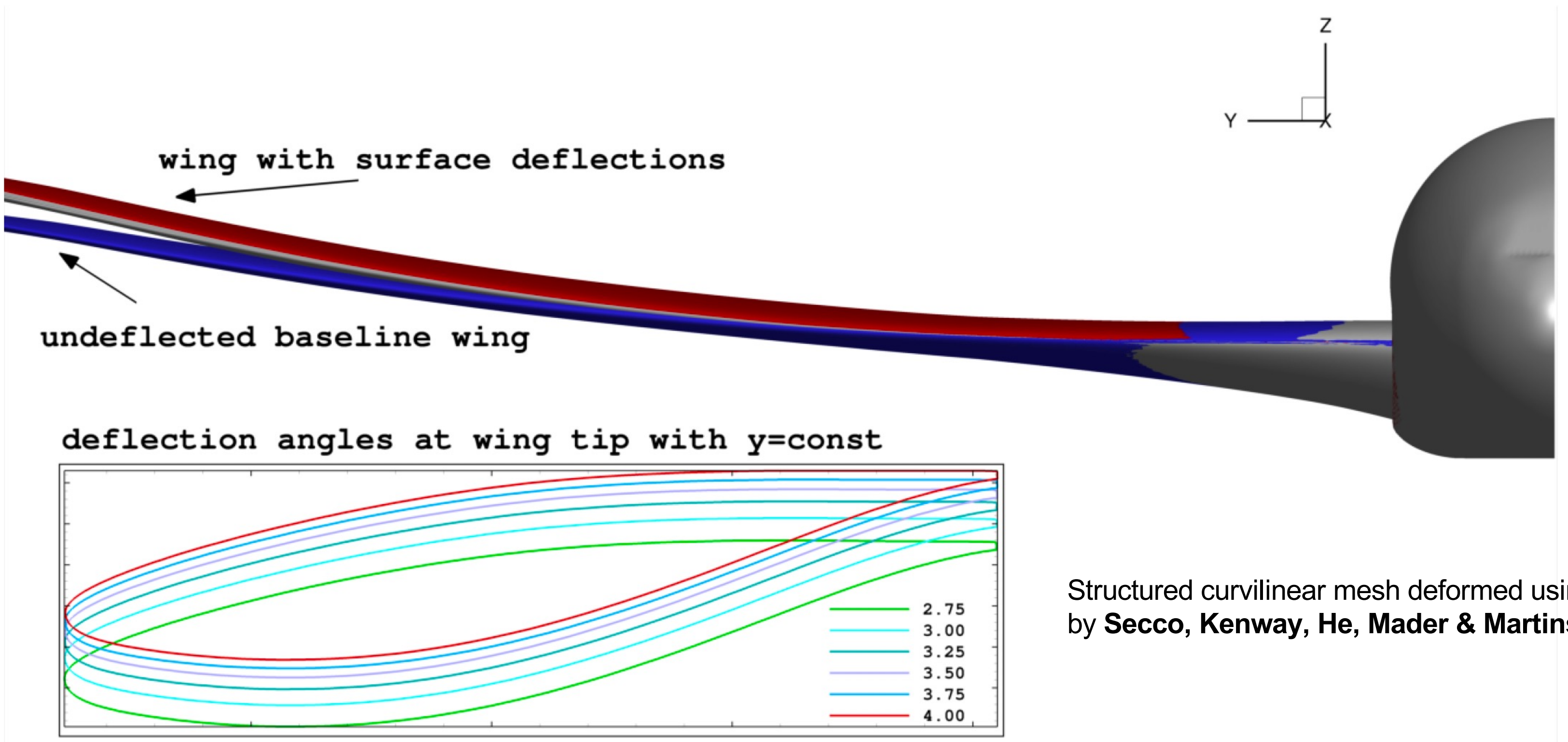


Streamwise velocity at distance $10^{-4}C_{ref}$ from surface

Angle of attack, $\alpha = 4^0$

Problem 2: Wing-body configuration

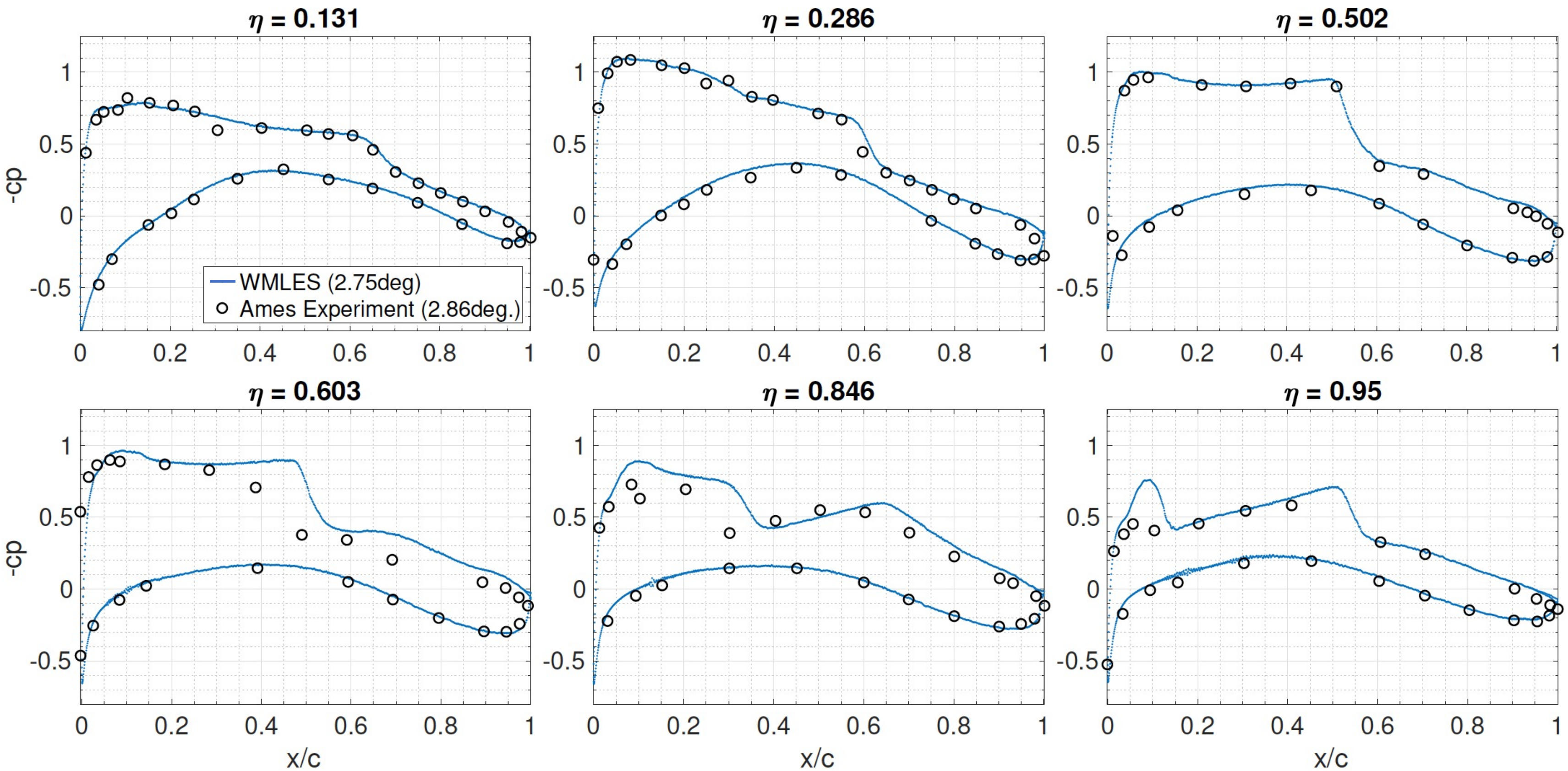
- Wing bending and twist different at each angle of attack; information provided at DPW6



Structured curvilinear mesh deformed using the algorithm by **Secco, Kenway, He, Mader & Martins (AIAA, 2021)**

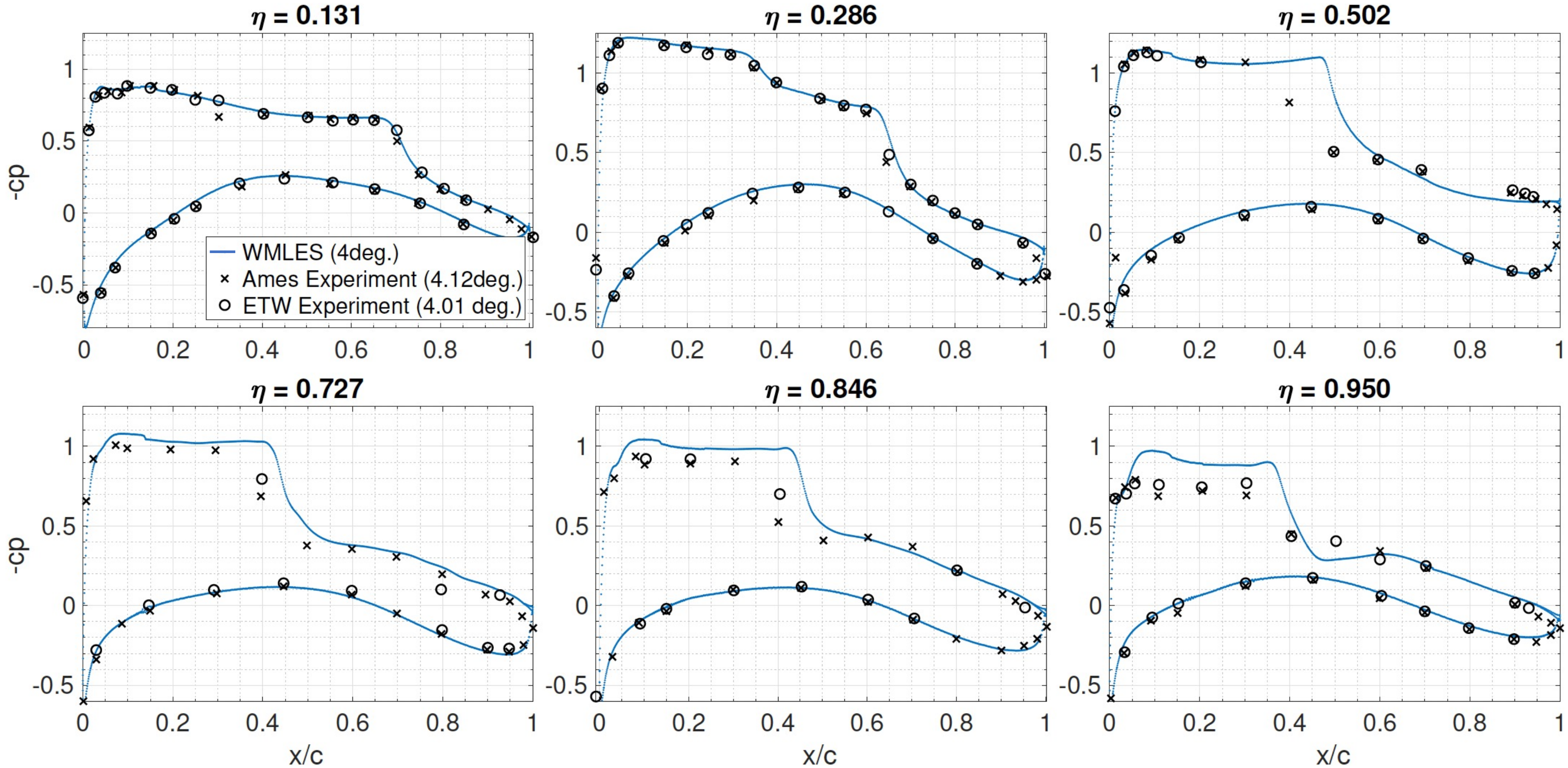
Problem 2: Wing-body configuration

- Cruise condition, $\alpha \approx 2.75; c_L \approx 0.51$



Problem 2: Wing-body configuration

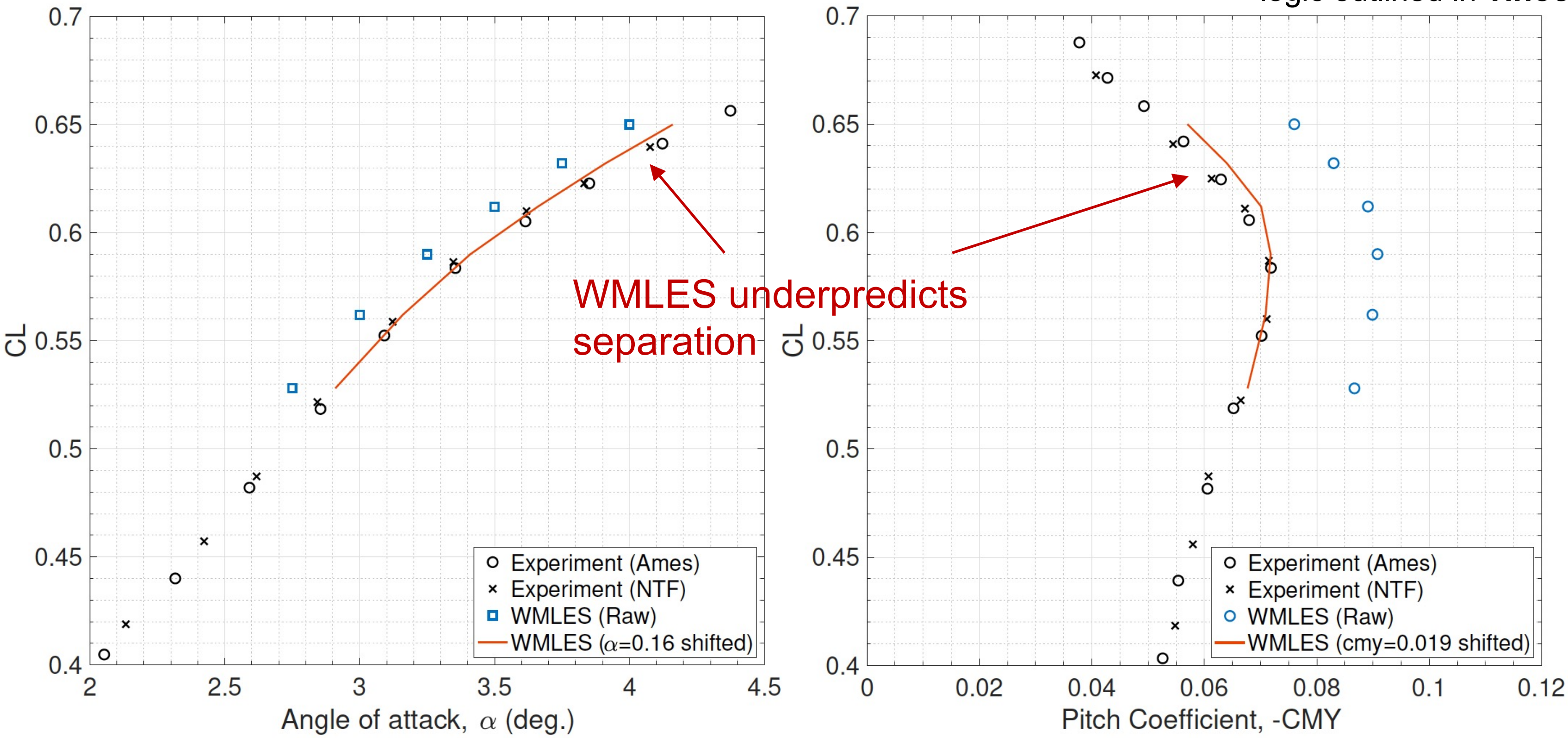
- Post-separation, $\alpha \approx 4.00; c_L \approx 0.625$



Problem 2: Wing-body configuration

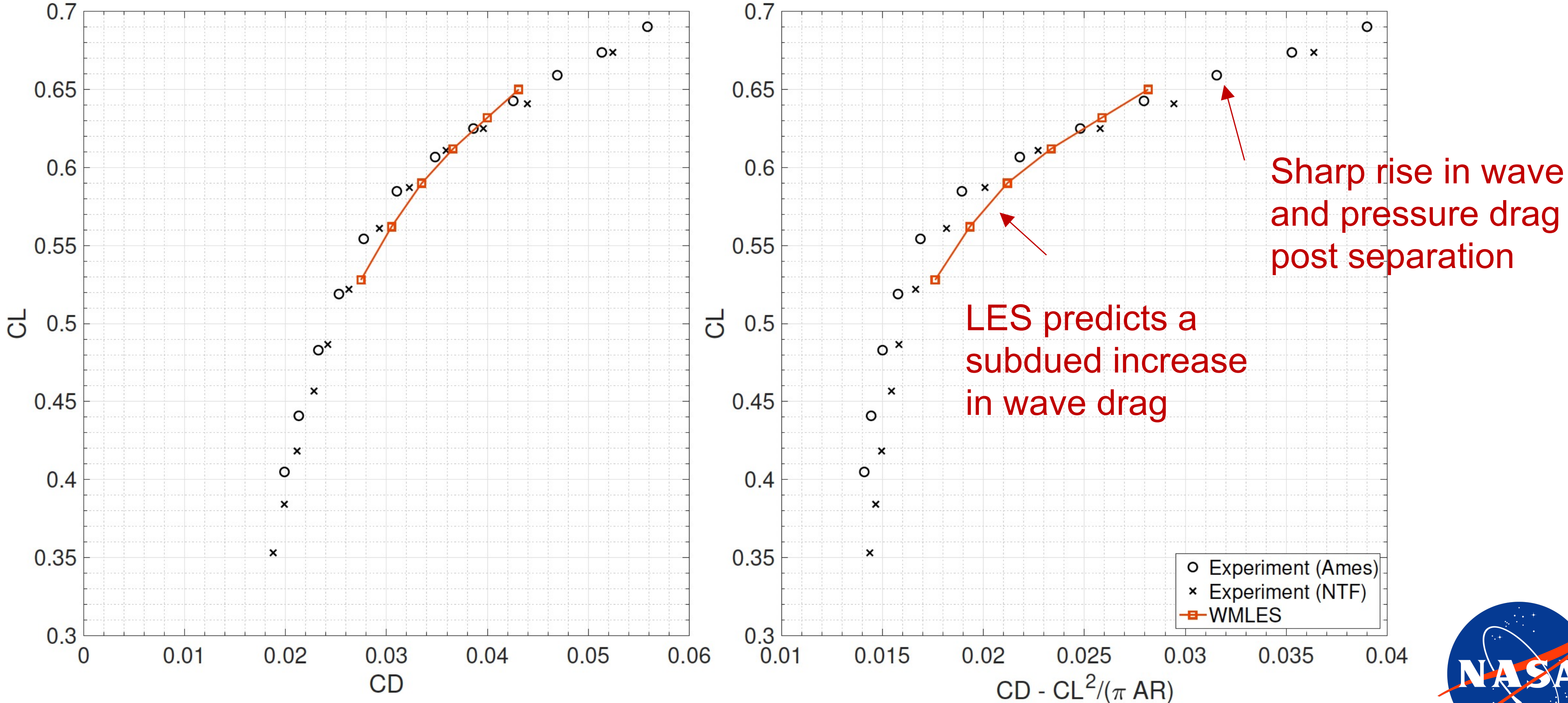
- Lift and Pitching moment

Note: the shifted solutions follow the logic outlined in **Tinoco (2020)**



Problem 2: Wing-body configuration

- Drag polar and wave-drag



Computational Costs

On **682 million grid points**, wing-body problem:

- Time step is approximately $8 \times 10^{-5}\ c_{ref}/U_{ref}$ (CFL = 1.25)
- Simulations run for more than $100\ c_{ref}/U_{ref}$
- Some advantage to initializing from WM-RANS steady state, but not much (about 10% acceleration to stationary state)
- On Intel Skylake architecture, each c_{ref}/U_{ref} takes **approx. 3000 core hours (120 NASA SBUs)**
- On more modern AMD Rome (EPYC) architecture significant reduction in wall time observed:
  - 128 AMD Rome nodes: **18 minutes per $\boldsymbol{c_{ref}/U_{ref}}$**

Conclusions

- WMLES performed for Wing-body CRM at transonic Mach numbers leading up to and including shock-induced flow separation and buffet
- Accurate prediction of lift-curve slope and onset of separation characterized by break in the pitching moment
- Ability of WMLES at predicting skin friction drag was assessed; reasonable agreement was observed with some sensitivity to SGS model constant near the LE
- Primary differences appear to be outboard where Reynolds numbers at shock-incidence are small (less than 10^6)
- Insufficient resolution results in underprediction of separation and shock strengths outboard:
    - Slight overprediction of lift
    - Inability to predict the rapid rise in pressure and wave drag

Outlook and future directions

- Unsteady analysis:
  - Substantially refined mesh (approx. 2 billion grid points); half-body
  - Shock-aware grid refinement; suction side refinement
- Transition sensitivity:
  - Representation of tripping – numerical roughness vs. obstructive trip dots
- Is tunnel blockage relevant?
- Aft-loading: what is it sensitive to? Do we need to wait for higher Reynolds number simulations?

Acknowledgements

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- For valuable discussions, special thanks to:
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  - Elisha Makarevich and Jacob Wagner (LAVA Team, NASA Ames)

- Computer time has been provided by NASA Advanced Supercomputing (NAS) facility

Questions?

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- Additional details provided in AIAA 2021-1439